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# Modelling and Simulation in the Design Process of Armored Vehicles

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## Abstract

The use of modern simulation tools in the development of new armoured vehicles permits shorter development times and a reduction in the number of prototypes. This paper shows the importance of virtual prototypes in the development process. Owing to more stringent protection requirements, the design layout of new vehicle concepts is possible only with the help of a complete vehicle simulation. Modelling techniques and simulation methods are presented by the example of mobility and mine protection analyses.

## 1 Introduction

The requirement for lightweight, armoured vehicles with a high level of protection and good mobility presents a major challenge to development engineers. Based on successes achieved over the past several years in the area of mobility and protection improvements, the focus is now on a drastic reduction in vehicle weight. For instance, unrestricted transport by C130 aircraft requires a transport weight of less than 17 tons, which is no longer practicable with today's vehicle platforms in light of increased protection and mobility requirements.

Today, new drive concepts, such as hybrid drives, and protection concepts, such as modular mine protection, are being developed for future lightweight armoured vehicle platforms. In the overall vehicle concept, suspension and mine protection are of key importance. The suspension is a determining factor for mobility and payload volume, the level of mine protection largely defines the vehicle structure and configuration of the crew compartment.

In developing mine protection characteristics, the design and tuning of the dynamic behaviour of the vehicle structure, along with occupant protection systems, are a demanding task which can be solved only in the context of the complete vehicle. The required test series and qualification trials, some of which are conducted with fully equipped vehicles, are very time-consuming and costly. Apart from the high cost pressure, the short procurement times sought by the customer for new vehicle systems call for a significant reduction in development times.

In order to meet these challenges, modern CAE methods must be consistently applied throughout the development process. Numerical simulation in this process is an important tool for the design layout as well as to substantiate vehicle development data. Generating virtual prototypes in an early phase of the process is an indispensable requirement, as the design and optimization of sub-systems is possible only within the complete vehicle system.

The following paper describes the use of simulation in the development process with the emphasis on mine protection and mobility analyses.

2 Virtual Prototype

The concept and layout phase for new vehicles today includes systematic studies of the capabilities, performance potential and technical limitations through simulation. This makes it possible to identify the key system components and to assess them in terms of cost and risk. Simulation techniques are primarily used in the following areas:

- Mobility (longitudinal, transverse and vertical dynamics)
- Structural design (stiffness)
- Mine protection (short-time dynamics)
- Ballistic protection (short-time dynamics)

A virtual prototype of the vehicle is generated from computation and CAD models as early as during the concept phase. Figure 1 and Table 1 gives an overview of the computation models and simulation tools used for this purpose.

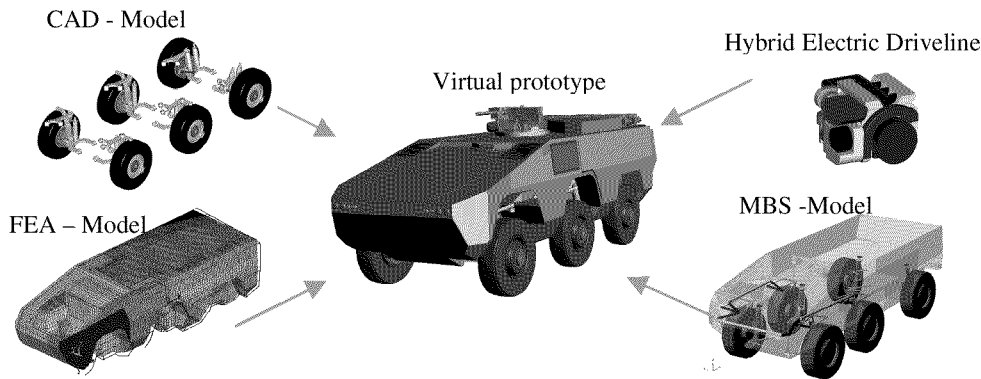


Figure 1: Virtual Prototype

Simulation	Model	Design Tool
Mobility Analysis	Multi Body System (MBS)	ADAMS/Car /1/
Power/Energy Management	Longitudinal Dynamic	Matlab /2/
Structural Analysis	Finite Elements Model	ANSYS /3/
Geometry/Assembly	CAD Model	Pro/Engineer /4/
Mine Protection	Finite Elements Model	LS/DYNA /5/
Human Dummy	Finite Elements Model	LS/DYNA
Ballistic Protection	Finite Elements Model	LS/DYNA

Table 1: Computation models and simulation tools

During the concept phase, the virtual prototype primarily consists of physical functions. As the development process progresses, geometries and components are increasingly added and detailed. The virtual prototype then describes the complete vehicle in geometrical, technical and functional terms. The geometrical CAD data, computation and simulation data of the virtual prototype are stored in a common product database (PDM) which serves as a work platform for the various development teams.

The digital mock-up (DMU) of the vehicle can be generated with the CAD models contained in the virtual prototype and the document structure (PDM). The DMU models describes the vehicle topologically and technically and serves the entire product development and design process as a database, e.g. to conduct installation, ergonomics and crash studies. Concurrently with the development activities, the virtual prototype may be integrated into tactical and operation simulations conducted by the contracting authority in order to verify vehicle requirements and, if necessary, adjust these requirements. Figure 2 and 3 show possible uses of virtual prototypes within the development process.

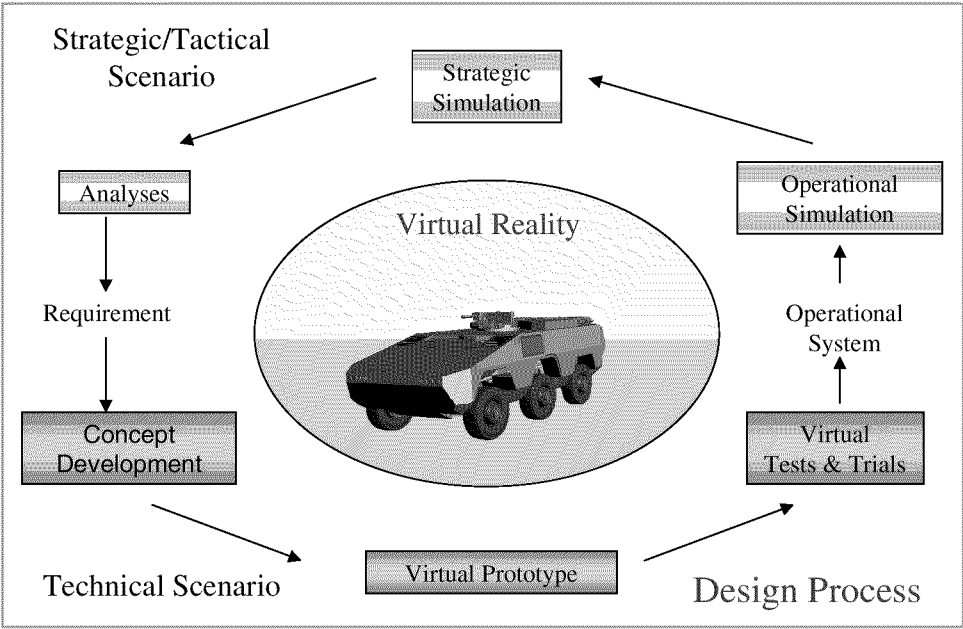


Figure 2: Use of virtual prototypes in the development process

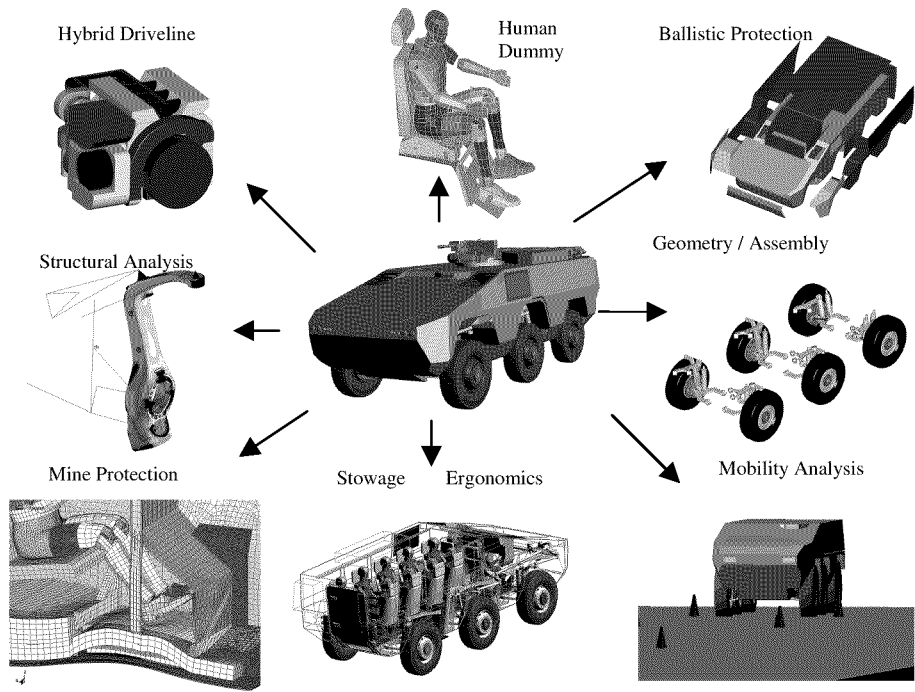


Figure 3: Use of virtual prototypes in analyses and design

### 3 Modelling and Simulation Tools

#### 3.1 Structural Analysis and Design

Finite element models linked to the CAD model are used to design the vehicle structure. The meshing of the intermediate surfaces with shell elements is most conveniently carried out with the assistance of the mesh generator of the Pro/Mesh CAD software. For linear structural analyses and modal analyses with ANSYS, this mesh quality will normally be sufficient. For explicit non-linear FE analyses, the models are meshed in the FE pre-processor in order to obtain a better mesh quality. The global design of the structure is initially based on standard load cases which are derived from measured data. For the local design of load introduction points, e.g. the suspension, load data are used from mobility analyses conducted with the MBS model. To optimize the structure in terms of stiffness and weight, topology and parameter optimizers provided by the ANSYS/OPT simulation tool are increasingly used.

#### 3.2 Suspension Analysis and Design

The multi-body simulation tool ADAMS/CAR developed specifically for the automotive industry is used for the preliminary layout of the suspension concept. The MBS tools provides a library of suspension concepts and evaluation functions which permit the efficient analysis of various concepts. Initially, a simple MBS sub-model of the suspension is generated to analyse and design the axle kinematics and spring/damper system. The design and tuning of the spring/damper system to match a variety of operational environments and trackway conditions is a demanding optimization task. Basically, a high level of ride comfort requires soft suspension tuning, whereas driving safety relies on a stiff suspension setting. In order to resolve this discrepancy, simulations increasingly use active suspension elements /6/.

The design layout of the suspension components is performed with the assistance of CAD and FE models. The CAD model reproduces the axle kinematics in order to carry out crash studies and to generate the envelope curve for all wheel positions. The envelope curve describes the wheel arch contour and thus defines the interior payload area of the vehicle. The FE model equally reproduces the axle kinematics in order to take account of the influence of elasticities and to optimize the component parts. Experimentally defined standard load situations are normally used to verify the strength of suspension components.

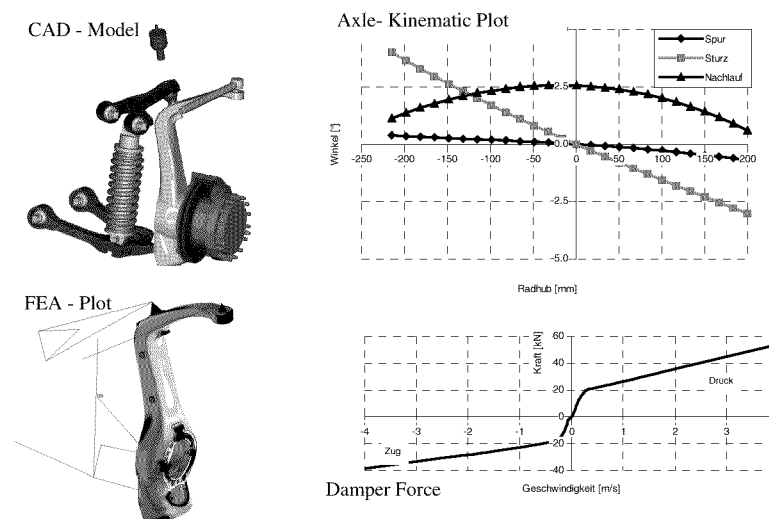


Figure 4: Modelling and Simulation in suspension design

A complete MBS vehicle model is generated to analyse the dynamic vehicle behaviour. The required data, unless already available, are derived from target value functions or measured data.

## 4 Simulation Techniques Used for the Development of Mine Protection

The design of mine-protected vehicles places high demands on the development. In case of a mine detonating under the vehicle, the floor structure must have a high level of stiffness in order to absorb as much energy as possible and at the same time ensure a low level of deformation of the floor into the crew compartment. On the other hand, the stiffness of the structure must not be such high that the floor structure breaks up and collapses due to material failure. The seat system itself and its connection to the vehicle structure must be of a certain compliance in order to keep the loads imparted to the occupants by forces and shocks as low as possible. All measures taken to protect the occupants must be highly responsive. After 0.3 milliseconds of a mine blast, the floor structure will already show local deformation. After 10 milliseconds, initial movements of the dummy caused by the introduction of forces and shocks can be observed. Initial vehicle movements occur after appr. 30 milliseconds.

In the area of vehicle development activities, mine protection measures generally relate to the following areas:

- Structural measures (floor deformation, introduction of forces and shocks, penetration behaviour)
- Occupant protection systems (seats, footrests, airbag, energy-absorbing elements)
- Interior equipment (padding, mounting of personal equipment, spall liner)
- Measures to preserve residual mobility

In designing mine protection systems, all measures must be well balanced. Computer simulation has proved to be an effective tool in developing mine-proof vehicles. The numerical simulation of the dynamic effects of a mine blast on the vehicle structure makes it possible as early as during the concept phase to predict the structural behaviour and to assess the effectiveness of different design approaches and their effects on the occupants.

### 4.1 Assessment Criteria

A key objective in vehicle development is the fulfilment of the occupant protection requirements in mine blasts. Generally, the following criteria are used to assess the mine protection level of a vehicle:

- Probability of occupant injury (DRI, dummy values, g loads, forces)
- Hazards caused by local failures (e.g. fuel leakage)
- Hazards caused by flying debris (secondary projectiles)
- Residual mobility

The probability of occupant injury is determined from stress values calculated in simulations with the assistance of dummies or in mine blast tests. The dummies used during these tests included the Hybrid III 50<sup>th</sup> dummies, which were developed and validated for the motor industry. Figure 5 shows the stress values of a dummy which are today evaluated with respect to the probability of injury.

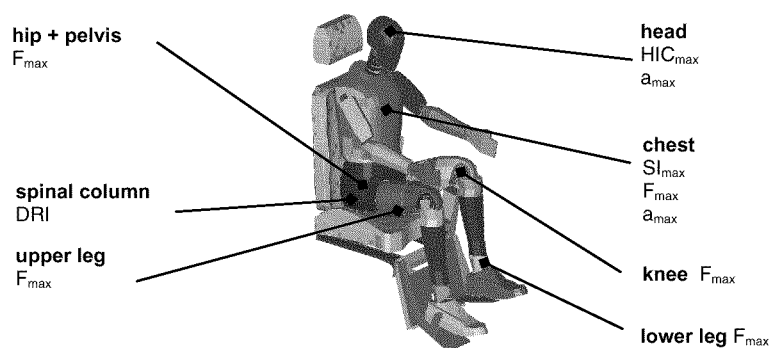


Figure 5: Stress values used to assess the probability of occupant injury

4.2 Model Harmonization With Blast Tests

Mine protection development activities include numerous blast tests conducted to verify and harmonize the simulation models. Experimentally determined are specifically data for material models, e.g. foam materials or welding seams and for pressure curves. The data and models obtained can be used to perform complete vehicle simulations for the purpose of verifying and optimizing mine protection. A comparison of the dummy stress values obtained with complete vehicle simulations with the values measured during qualification tests shows a high level of agreement. Figure 6 shows a comparison of the calculated and measured vertical g loads acting on the pelvic area of a Hybrid III dummy during a mine blast under a vehicle.

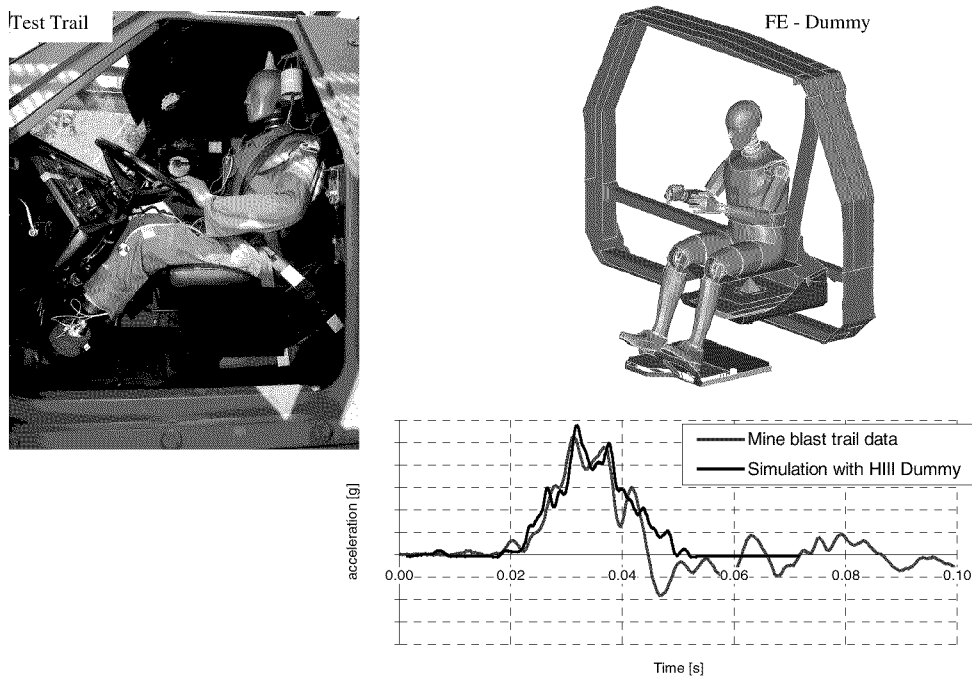


Figure 6: Comparison of calculated and measured vertical g loads in the pelvic area of a Hybrid III dummy

4.3 Mine Simulation

An FE computation model is based on a CAD model of the vehicle structure. During the development phase, the calculation engineer and design engineer consult each other to make sure that the CAD model of the vehicle structure can be meshed easily. In this way, it is possible to avoid the frequently considerable effort required to generate an intermediate surface model capable of being meshed. The generation of intermediate surfaces from the ProE data is possible with the assistance of the ProENGINEER module ProMECHANICA. For meshing and the further set-up of the computation model, the FE program ANSYS is used under the ANSYS/LS-DYNA user interface. This is where the vehicle equipment relative to mine protection (e.g. floor liner, stiffening profiles, tank, transfer boxes, etc.) are added, the contacts of the component parts among one another are defined as well as loads are applied and further boundary conditions defined. Also carried out as part of ANSYS is the installation of the dummy in the model as well as the correct orientation of the limbs.

A great deal of attention must be given to those components that are located between the inner and the outer vehicle floor. These components, such as the transfer box, tank or floor liner, reduce the load on the mine protection floor by their very mass (shock absorption) when they are hit and accelerated by a dynamically denting floor structure.

These components must therefore be included in a simulation. However, in conjunction with the simulation, they also represent a good opportunity for design and optimization.

For the actual calculation of the model, the explicit, non-linear equation solver LS-DYNA is used. For the usual model sizes of 100,000 – 300,000 elements, LS-DYNA requires approximately 20-30 hours on a workstation (SGI OCTAINE2) for a computation period of 20 milliseconds, depending on mesh refinement and model structure. Owing to the relatively small storage capacity requirement of LS-DYNA, such an analysis can also easily be performed on a well-equipped PC.

The evaluation of the computation results is subsequently carried out in the LS-POST processor. LS-POST also includes the output and evaluation of the dummy stress values.

The FE model for the explicit dynamic analysis shows a very high level of detail and a high mesh quality. This FE model can therefore also be used without any major effort to conduct implicit static structural analyses or modal analyses.

#### 4.4 Load Introduction

The level of protection of the vehicle is normally specified by the contracting authority. It can be used to calculate the effective energy, the local and time-related impulse of the mine and to derive load conditions for the simulation. Loads created by a mine blast are introduced into the vehicle structure in the form of a pressure distribution on the vehicle floor variable in terms of time and location. In this case, time-variable pressure loads are applied to the vehicle underfloor in a radial pattern starting from the centre of the blast, Figure 7.

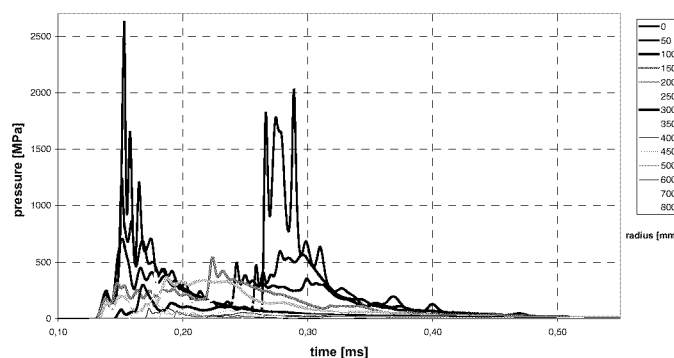


Figure 7: Pressure distribution of a mine blast at 500 mm distance from the floor (freely positioned in a steel collar)

The time-variable pressure distribution is determined as a function of type of mine, type of emplacement, soil condition, underbody ground clearance, shape of the underbody and radial distance from the centre of the blast. The pressure distribution is calculated by means of the SHAMRC program, an explicit simulation program (2D-Euler Code) [7] operating with higher-order finite differences. The calculated mine load cases have been validated through simulated blast tests with steel plates and vehicle structures.

In the complete vehicle simulation, the decoupling between the load simulation and then structural response analysis is possible, in those cases where loads occur instantaneously as in the case of mine blasts, when boundary conditions (ambient geometry) vary only slightly during the period of load introduction. While the dynamic vehicle floor deformation takes on the maximum value after appr. 1.5 to 3 ms, the pulse load of a mine laid on the surface will have reached almost its final value after 1 ms. The peak pressure at the centre of the blast even has only an effective period of up to 0.3 ms after the start of the blast.

The interaction between the propagation of the detonation fumes and underfloor deformation can therefore be neglected in a first approximation. This permits the separation between load simulation and simulation of the structural response.



4.5 Example: Mine Blast Under Driver’s Station

In a mine blast, the vehicle outer floor is dented instantaneously. Components (e.g. propeller shafts, transfer boxes) located directly above the vehicle outer floor are thus subjected to g loads and partly impart the deformation to the inner floor (Figure 8). Depending on the position and orientation of the feet or lower legs, injuries to occupants may result if the necessary safety distance from the inner floor is not sufficient or if the contacting structure is too stiff.

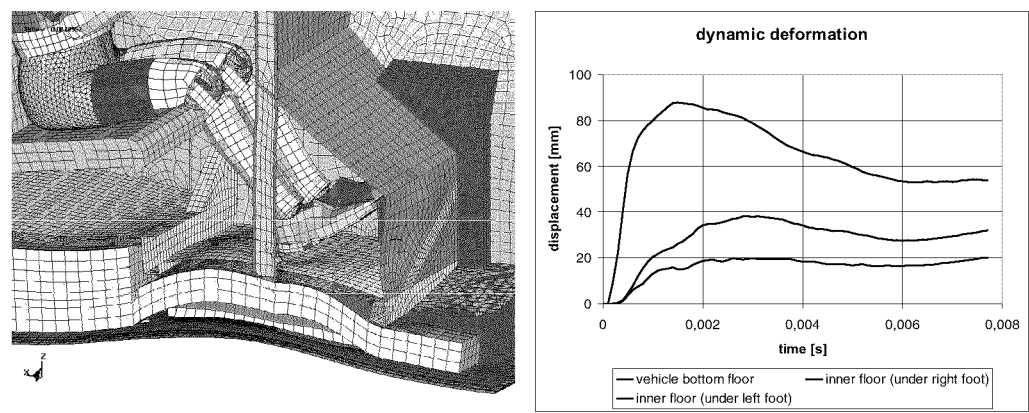


Figure 8,9: Deformation condition after a mine blast in the driver’s foot area

Figure 9, the structural response of the vehicle outer floor and inner floor to a pulse-like mine blast. As can be seen, the inner floor of the vehicle is still heavily deformed owing to the coupling effects in the intermediate floor area. Figure 10 shows the effects on the driver’s feet resulting from the deformation of the inner floor with the assumed safety distance and the assessment criteria. While the left foot of the driver is not notably stressed, the right foot is exposed to distinct but still negligible loads. Based on such considerations, the blast simulations make it possible to largely analyse the interaction between the vehicle outer floor, intermediate floor components and inner floor in order to be able to take suitable measures for structural optimization. The dummies are used to define the necessary safety distance (footrests) between feet and inner floor or to determine non-critical crew stations.

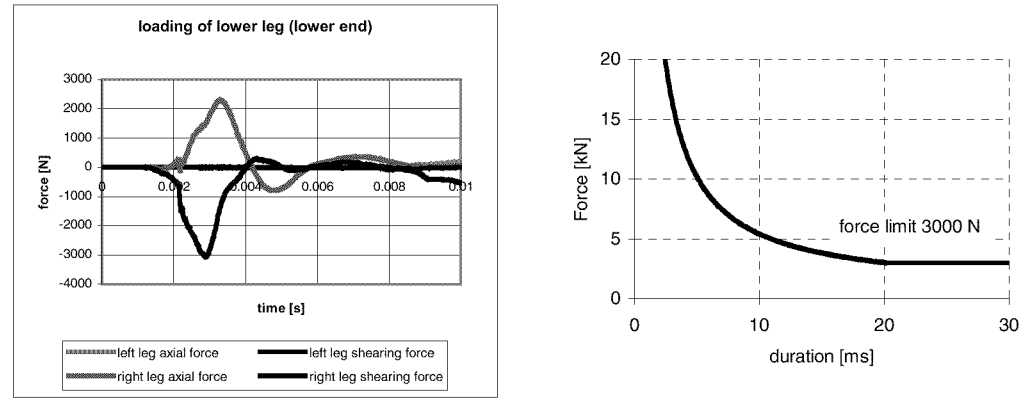


Figure 10: Forces acting in the lower area of the driver’s lower leg in a mine blast underneath the driver’s feet and assessment criteria

5 Simulation and Analysis of Vehicle Dynamics and Mobility

In the concept phase of vehicle development, driving dynamics and mobility analyses are of special importance in order to determine the loads, required spring travel and steering angles. The space claim of suspension and steering in turn determines the payload area in the vehicle interior and thus the total vehicle concept.

Real test tracks are modelled to simulate and assess the mobility of the vehicle. The geometrical description and discretization of the virtual road and terrain profiles as well as single obstacles are performed with FEM. The surface characteristics, such as coefficient of friction and compliance, are allocated to the individual elements.

In future, load cycles will also be determined on virtual test tracks in addition to mobility assessments. During the development, the calculated load cycles are to be used for structural analyses, computational component part life assessments to activate test stands.

## 5.1 MBS - Model

The fully parametric MBS complete vehicle model, Figure 11, is composed of the following sub-models and functions, using ADAMS/CAR:

- Chassis and suspension components
- Axle and steering kinematics
- Drive model (torque control); with differentials
- Tyre model
- Spring/damper elements
- Active suspension elements with controllers
- Driver model (steering and speed controller)
- Trackway profiles (terrain courses, bad roads, single obstacles)

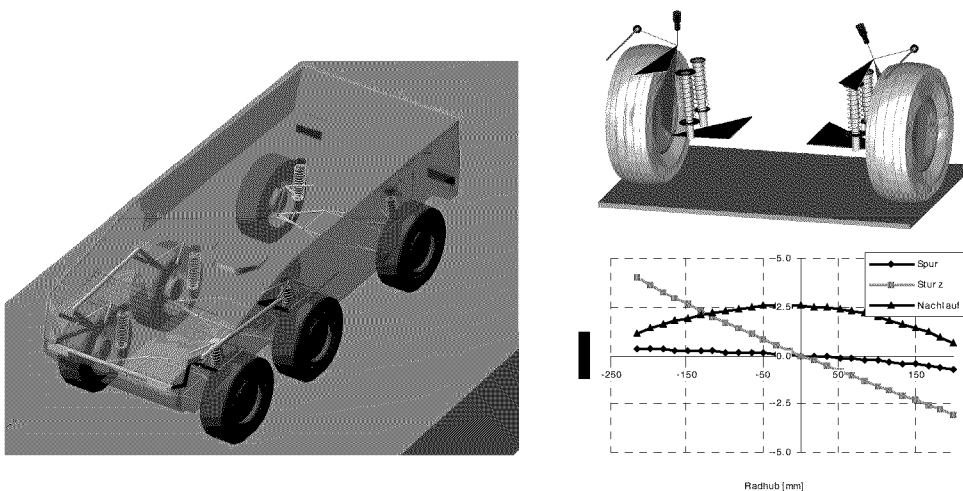


Fig. 11: MBS-Model 6x6 Off-Road Vehicle

The individual axle systems are built up from the kinematic points, the structures, joints and force elements. The spring/damper system can be replaced with active elements using control algorithms.

In the case of the tyre model, the measured data of the tyre manufacturers are used in the Pacejka 89 format. It is possible to provide a 3D contact between the contact patch and road profile. The various 3D trackways are reproduced with triangular elements.

The driveline is reproduced from the wheels to the transmission output shaft. Lockable transverse and longitudinal differentials are used. The torque acting on the transmission output shaft is controlled by the driver model.

The driver model is an intelligent model and controls the steering angle, input torque and brake forces.

The individual systems are easy to replace and modify. During the concept phase, it is possible for example to assess and select centre-of-gravity positions, wheelbases, different axle concepts and suspension systems.

5.2 Assessment Criteria

The mobility of a vehicle is generally assessed at the maximum possible average speed on specified terrain courses. The maximum off-road speed is generally limited by traction, input torque, driving safety and ride comfort.

When obstacles are to be negotiated, the speed at which a maximum driver’s station vertical acceleration of 2.5 g occurs, the pitch behaviour and vibrations under bad-road conditions are the subject of the assessment. The reference criteria are data obtained from similar off-road vehicles.

In terms of handling, the objective is neutral or a slight understeer behaviour. The roll reactions are to be minimized. Also desirable is a broad and easily controllable handling limit. This assessment is based on the methods used by the commercial vehicle and car industry.

5.3 Simulations

The following capabilities are verified through mobility analyses:

- Negotiation of single obstacles (step, ditch, ridge)
- Movement on rolling terrain (sinusoidal, offset sinusoidal)
- Bad-road conditions (Belgian block, washboard surface)
- Movement on soil with limited load-bearing capacity

The dynamic driving behaviour in double lane changes, fast cornering, braking in bends, is simulated on different coefficients of adhesion.

5.4 Results – Mobility analyses

Figure 12 shows a comparison of the calculated and measured vertical g loads acting on the driver’s station of a 6x6 vehicle when crossing a single obstacle at 60 kph. The use of highly effective bump stops keeps the vertical acceleration below the allowable value of 2.5 g.

Figure 13 shows the cornering behaviour of a 6x6 off-road vehicle for different speeds on dry and wet pavements. Following optimization of the axle kinematics, slight understeering was achieved for all required load conditions. The vehicle remains safely controllable at the handling limits.

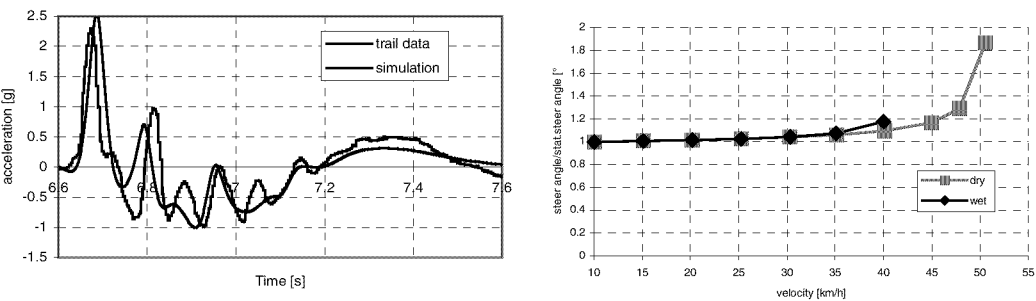


Fig. 12,13: Harmonisation simulation-measurement Single obstacle at 60 kph , Steering behaviour

Figure 14 shows the mobility required for off-road vehicles with the vehicle moving on a ramp at 40 kph. The virtual tuning of the spring/damper system (including the hydraulic bump stops) and the required wheel travel was defined during the mobility simulation runs.



Figure 14: Ramp 1.5m at 40 kph; virtual and physical prototype

Driving safety and ride comfort of a vehicle are essentially influenced by the spring/damper system. Figure 15 shows the effect of a passive and partially active spring/damper system on bad roads and on a sinusoidal course. The simulation shows that the use of active spring elements can significantly reduce the level of vibration and pitch movements of the vehicle. On terrain courses, this helps achieve a greater average speed.

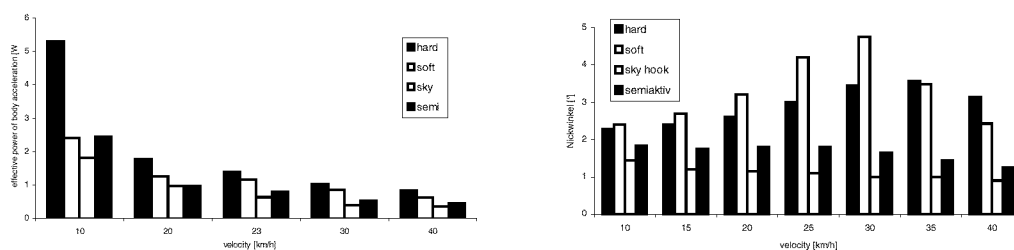


Fig. 15: Comparison of the effect of an active (sky hook controlled) and passive spring/damper systems on bad roads

## 6 Summary and Outlook

Simulation today is an integral part in the development process for new armoured vehicles. The use of simulation tools makes the result of a development predictable and design solutions can be verified or changed or optimized early on in the program. The identification and quantification of discrepancies permit fast decisions and trade-offs between different approaches.

This paper shows the importance of virtual prototypes in the development process to reduce development cost and times. Owing to more stringent protection requirements, the design and optimization of new light armoured vehicles is possible only with the assistance of complete vehicle simulations. To design the suspension and assess vehicle mobility, simulation runs are conducted with verified vehicle models and virtual test tracks. Mine protection is designed and assessed with the assistance of complete vehicle simulations using FE dummies.

The plans for the future are to replace partial qualifications of vehicle variants with simulations in order to further reduce the number of required prototypes. At this time, it is not yet foreseeable that prototypes will become totally unnecessary, as numerical simulations can only answer questions that are explicitly factored into the model. No direct statements can be made on manufacturing influences, spreads in material characteristics and test conditions. The reliability of the solutions calculated can however be assessed with stochastic simulations, e.g. based on the Monte-Carlo Method [8].

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